Ph.D. Synopsis Report

On

Design of Graphene based THz 6G Antennas

Submitted by:

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1. **Title :-** Design of Graphene based THz 6G Antennas.

2. Introduction

2.1 Motivation

- Future wireless technology requires the wide bandwidth and hence the higher data transfer rate. This can be possible to achieve with the utilization of THz spectrum (0.1−10 THz). This motivates to learn and implement the microscale sized THz antennas.
- Microscale size of THz device cannot allow to refabricate them easily if one wants to change the device response. An electronic tunability is required for THz devices.
- This research aims to overcome the low quantum efficiency of thin-film solar cells. This is achieved through the design of nanoreceptors that utilize plasmonic light trapping to significantly enhance absorption and, consequently, the overall solar energy conversion efficiency.

2.2 THz Frequency spectrum

The terahertz (THz) frequency band ranges from 0.1- 10 THz and lies in between infrared and millimetre wave band in the electromagnetic frequency spectrum as shown in Figure 1.1. The latest technology is moving towards the implementation of terahertz (THz) systems [1], [2]. The potential applications of THz spectrum in medical, defence and wireless systems are being investigated due to its; non-ionizing nature, capability of providing the large bandwidth and radiations with the characteristics like infrared and microwaves [3]–[5].

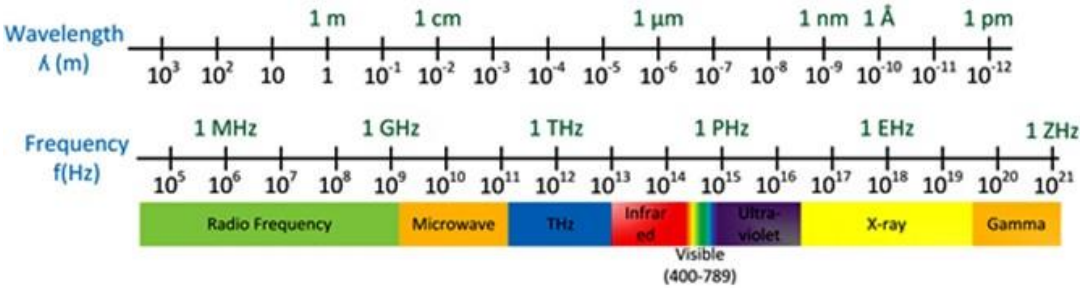

Fig.1 The Electromagnetic spectrum

The implementation of wireless systems utilizing THz spectrum is the objective of future developments [6]. Advancements in wireless technology are seeking the advanced antennas with multiple features like high gain and radiation efficiency, reconfigurable frequency response and radiation pattern.It is expected that utilization of THz spectrum will be providing the large channel capacity and hence the higher data transfer rate can be achieved. The development of THz antennas is on the way and researchers are developing them with the different features like with different polarizations with desired gain and radiation efficiency and with reconfigurability in radiation pattern and frequency response.

2.3 THz Antenna

An antenna is a transducer that converts electrical energy into electromagnetic radiations and vice versa. The terahertz (THz) antennas, which have features of small size, wide frequency bandwidth and high data rate, are important devices for transmitting and receiving THz electromagnetic waves in the emerging THz systems. However, most of THz antennas suffer from relatively high loss and low fabrication precision due to their small sizes in high frequency bands of THz waves.THz antennas are categorized as metallic antennas, dielectric antennas and new material antennas.At present, a large number of applications are gradually migrating from computers to wireless devices such as mobile phones, which are convenient to carry and operate in real time, but this situation also leads to a rapid increase in data traffic and lack of bandwidth resources. According to statistics, the data rate in the market in the next 10 to 15 years is likely to reach Gbps or even Tbsp. At present, THz communication has obtained Gbps data rate, while the Tbsp. data rate is still in an early stage of development [4]-[5] has listed recent progress in Gbps data rate based on THz band and predicted that Tbps can be obtained by a polarization multiplexing. Therefore, to increase the data transmission rate, a feasible solution is to develop a new frequency band, which is a THz electromagnetic wave at the “blank area” between microwaves and infrared light.

2.4 THz radiator material

With new technical advancements in semiconductor and material science technologies, there has been an increase in efforts towards realization of suitable material in the THz. High

precision in antennas is considered to be a critical component of any communication system, whereas using a suitable material to build up the same plays a key role in achieving such high precision. The selection of a suitable material having minimum propagation losses is a challenging task in designing an efficient antenna. On the basis of radiator material, THz antenna can be classified as: [7]–[20][21].

1. Metal radiator
2. Graphene radiator
3. Dielectric radiator

The metal radiators have high electrical conductivity in RF and microwave frequency, but it does not remain same at THz frequency. At THz frequency range, ohmic resistance plays a dominant role in contributing to the metallic and surface waves losses and hence making it difficult task to design such antenna. The antenna with graphene based radiator provides the re-configurability in different antenna parameters (such as frequency response and radiation pattern) but it suffers from poor radiation efficiency and low gain. Use of dielectric resonator based radiators is the easiest solution to all these problems. It is due to the natural potential of ceramic based radiators such as, absence of metallic losses, able to create multiple mode patterns, absence of surface wave losses and easy to achieve wider impedance bandwidth.

2.5 Tunability/reconfigurability

A tunable antenna, also known as a reconfigurable antenna, it is capable of dynamically modifying its frequency and radiation properties in a controlled and reversible manner. Graphene [7] is a promising candidate for the design of tunable devices. The graphene material introduces an excellent tunability to the antennas in THz regime. Graphene-based frequency reconfiguration mechanisms for antennas are achievable through the incorporation of DC voltage lines that injects an electric field. Due to this, the chemical potential of graphene is varied to alter its surface conductivity (σ_g) due to injection of the carriers and tunable frequency response is achieved. From the Kubo's formula the intraband and interband conductivities are defined using Drude's model as in equation.

$$\sigma_g(\omega) = \frac{j2e^2K_BT}{\pi\hbar^2(\omega + j\tau^{-1})}\ln\left[2cosh\left(\frac{\mu_c}{2K_BT}\right)\right] + \frac{e^2}{4\hbar^2}\left[\frac{1}{2} + \frac{1}{\pi}\left[arctan\left(\frac{\hbar\omega - 2\mu_c}{2K_BT}\right) - \frac{j}{2\pi}\ln\left[\frac{(\hbar\omega + 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + 4(K_BT)^2}\right]\right]\right]$$

Here, ω is the angular frequency, and e, K_B and $\hbar$ are electron charge, Boltzmann constant, reduced Planck's constant, respectively. According to the Pauli exclusion principle, the THz frequency domain at room temperature can be neglected as $E_f \gg K_BT$ and $E_f \gg \hbar\omega$, the contribution of the interband conductivity to the surface conductivity can be ignored at the lower THz region. The chemical potential of graphene is related to bias voltage as $V_g = \frac{e\mu_c^2 h}{\pi h^2 v_f^2 \epsilon_0 \epsilon_r}$. Here,$\epsilon_0$is the vacuum permittivity.

3. Literature Review

A comprehensive review of existing literature reveals various approaches to integrating graphene for enhanced THz antenna performance, categorized by key design functions:

3.1 Reconfigurability and Polarization

Research confirms the utility of graphene in achieving dynamic characteristics:

- **Dual-Band & Circular Polarization:** Early work focused on dual-frequency circularly-polarized patch antennas for applications like GPS (Nasimuddin et al., 2010). More recently, reconfigurable circularly polarized hemispherical Dielectric Resonator Antennas (DRA) have been explored using plasmonic graphene strips, achieving high-gain performance (7 dBi) in the 45–92 THz range for MIMO communications (Malhat et al., 2022). Furthermore, a polarization controlling approach has been successfully implemented in a reconfigurable microstrip graphene-based antenna (Kiani et al., 2020).

3.2 Ultra-Wideband (UWB) and Band-Notch Functionality

The ability to create a selective filtering function within a wideband spectrum is vital for interference mitigation:

- **Tunable Band-Notch:** The integration of graphene nanoribbons allows for obtaining a tunable band-notch feature within an ultrawideband THz antenna (Sharma et al., 2020).
- **Compact UWB Design:** Researchers have also presented compact UWB monopole antennas that achieve a tunable notch bandwidth/frequency ratio, covering a range of 6.13–12.94 THz with a gain of 6.60 dBi (Srivastava et al., 2021).

3.3 MIMO and Multi-Port Configurations

Addressing the massive connectivity demands of 6G requires robust MIMO designs:

- **MIMO with Diversity:** Proximity-coupled two-port multi-input-multi-output graphene antennas have been designed to incorporate pattern diversity for THz applications, operating around 1.76–1.87 THz with a gain of 4.45 dBi (Varshney et al., 2019).
- **Wideband and High Isolation:** Designs include fractal-loaded planar Super Wide Band four-element MIMO antennas (0.72–10 THz, 4.45 dBi gain) (Das et al., 2021), and easily extendable four-port MIMO antennas featuring improved isolation and a wide bandwidth (1.5–10 THz) with a high gain of 11 dBi (Raj et al., 2021).
- **Micro-Scaled MIMO:** Micro-scaled graphene-based tree-shaped wideband printed MIMO antennas have also been proposed using materials like polyimide and copper (Babu et al., 2022).

3.4 Radiation Pattern Control and Filtering

Beyond frequency tuning, controlling the radiation pattern and filtering characteristics is crucial:

- **Radiation Pattern Improvement:** A method was outlined to null-fill the H-plane radiation pattern of a graphene patch THz antenna by utilizing a branch feeding microstrip line (Moradi and Gholamreza, 2019).
- **Frequency Selective Surfaces (FSS):** The concept of tunable THz antennas integrated with polarization-insensitive frequency selective surfaces has been explored, demonstrating a pathway to achieving specific frequency filtering capabilities (Das and Varshney, 2021).

The design of terahertz (THz) antennas for 6G communication systems has gained significant attention in recent years. Graphene, a two-dimensional material with exceptional electrical, thermal and mechanical properties has emerged as a promising material for THz antenna design. Graphene based THz Antennas provides high gain, wideband bandwidth and electronic tunability features. Extensive research has been conducted on THz and Graphene based antennas. Recent work covers tunable UWB antennas, Graphene based MIMO systems, Pattern Diversity antennas, dielectric resonators antennas, THz absorbers, and self duplexing antennas.

The reviewed literature highlights gaps in tunability, filtering, efficiency, enhancement and multifunction integration areas directly addressed by this research.

4. Research Plan

The primary objectives of the proposed research are:

- To design and model graphene-based THz antennas for ultra-high frequency operation.
- To analyze the plasmonic behavior of graphene for tunable THz antenna performance.
- To design solar nano-receptors capable of efficient nanoscale energy harvesting.
- To improve antenna gain, bandwidth, tunability, and radiation characteristics using hybrid structures.
- To simulate and optimize the proposed antenna system using CST, HFSS, or COMSOL.
- To evaluate performance metrics for 6G and THz communication environments.

5. Methodology

The following points detail the implementation strategy for each core research objective as follows

5.1. Tunable Dual-Band Operation and Frequency Ratio Control

The initial phase focuses on developing a dual-band antenna with dynamic control over its frequency separation.

- Frequency Ratio Establishment: The baseline frequency ratio between the two resonant modes is obtained through the proper placement of a graphene loop and a slot within the antenna structure. This structural geometry is critical for establishing the two distinct resonant paths.
- Electronic Tuning Mechanism: The capability for Frequency ratio tuning is achieved by introducing a change in the chemical potential (μc) of the graphene loop. Varying the μc via an external DC bias alters the graphene's surface conductivity (σg), which effectively shifts the resonant frequency of the associated mode to achieve real-time tunability.

5.2. Tunable MIMO and Self-Duplexing Capability

The same principle of electronic control is extended to achieve system-level functionality.

- Control Implementation: The functionality of MIMO (Multi-Input Multiple-Output) and Self-duplexing is achieved by utilizing the change in the chemical potential of the graphene loop. This suggests that the phase, frequency, or isolation properties necessary for these applications are controlled by dynamically adjusting the graphene's electrical state.

5.3. Tunable Dual-Band Response via Surface Plasmon Resonance

This phase targets a specific mechanism for tuning: surface plasmon resonance.

- Placement Strategy: To achieve the dual band tunable response by merging the resonance of the surface plasmon in the fringing field, a graphene sheet is strategically placed at the position of the null of the near field region. This placement maximizes the coupling of the antenna's fringing field to the graphene's surface plasmons, enabling their resonance to be controlled.

5.4. Ultra-Wideband (UWB) Response with Tunable Band Notch

To enable flexible spectrum utilization, a band-notch function is introduced into a UWB antenna design.

- Notch Implementation: For creating the tunable band notch in the UBW range, a graphene loop is placed at the slotted antenna radiator. The graphene loop acts as a tunable resonant element, which can be dynamically adjusted to block or notch out a specific frequency band within the wide UWB spectrum.

5.5. Tunable Filtering Characteristics and Efficiency Enhancement

The methodology includes dedicated steps to improve the overall performance metrics.

- Efficiency Enhancement: A double graphene loop is used for the objective of obtaining a tunable filtering THz antenna. The use of two graphene loops is specifically employed for the purpose of increasing the Radiation efficiency of the antenna.

5.6. Nanoreceptor Design for Light Trapping

The final, distinct objective requires a different structural approach for a non-communication application.

- Light Trapping Structure: To fulfill the objective of the Design of nanoreceptor for light trapping in the solar frequency range, a graphene disc is applied beneath the substrate of the antenna. This design leverages the plasmonic properties of the graphene disc to enhance light absorption, typically in a thin-film solar cell structure.

The methodology includes:

- Step 1: Graphene sheet modeling and conductivity analysis.
- Step 2: Design of THz graphene antenna using plasmonic principles.
- Step 3: Development of nanoscale Solar Light-Trapping Nano-Receptor layer (SLTNR).
- Step 4: Integration of SLTNR with the antenna substrate.
- Step 5: Electromagnetic simulation of the hybrid model.
- Step 6: Prototype fabrication using nanofabrication techniques.
- Step 7: THz characterization and performance testing.
- Step 8: Comparative evaluation with conventional THz antennas.

6. Expected Outcomes of the Research

The expected outcomes of this research represent a significant advancement in both communication technology and sustainability, aiming to move beyond traditional fixed-performance systems. The central achievement will be the realization of Improved radiation efficiency and tunability using graphene plasmonics, offering unprecedented dynamic control over antenna properties for adaptive networks. This tunability will ensure Compatibility with future 6G smart devices, IoT sensors, and RIS (Reconfigurable Intelligent Surface) surfaces, which are foundational to next-generation wireless infrastructure. Furthermore, a crucial goal is the integration of disparate functionalities into a Novel integrated model combining communication and energy harvesting, specifically by coupling the THz antenna with an energy-absorbing nanoreceptor. This integration is designed to produce a fully energy-autonomous THz antenna system, eliminating reliance on external power and simplifying deployment. Ultimately, by utilizing efficient, electronically controlled graphene components, the entire system is designed to operate under the paradigm of Environment-friendly and sustainable antenna operation, minimizing energy footprint and contributing to greener technology.

7. Significance of the Study

The significance of this study is rooted in its direct contribution to enabling the next generation of wireless communication, specifically the development of 6G communication systems. As future wireless technology mandates wide bandwidth and higher data transfer rates , the research is critical for successfully utilizing the Terahertz (THz) spectrum (0.1 - 10 THz), which is the objective of future developments. The central technical significance is addressing the practical limitation that microscale THz devices cannot be easily refabricated; the study solves this by introducing essential electronic tunability using graphene, a key material that offers excellent dynamic control in the THz regime. The resulting graphene-based THz antennas are highly suitable for 6G systems by providing high gain, wideband spectrum, and complex, configurable functionalities such as dual-band frequency ratio tuning, MIMO, Self-duplexing, and tunable filtering characteristics. This research not only advances wireless technology but also holds future scope for implementation in critical non-communication fields, including biomedical and sensing applications.

8. Conclusion

Graphene based THz antennas provides high gain, wideband spectrum and electronic tunability which will be suitable for 6G wireless communication systems. Along with these various functionalities can be achieved with the help of graphene loaded THz Antenna like Dual band frequency ratio tunning, MIMO and Self duplexing capability, Band notch creation in UWB using resonant/non-resonant graphene, tunable filtering characteristics. Future scope of these types of antennas is in testing and validation of graphene-based THz antennas, electronic integration, biomedical and sensing.

9. Chapterization

Chapter 1 – Introduction

This chapter provides a comprehensive introduction to the motivation behind using the terahertz (THz) spectrum for future 6G communication systems. It explains the increasing demand for wide bandwidth, high data rates, and miniaturized antenna

systems, and highlights the limitations of conventional materials at THz frequencies. The chapter introduces graphene as a tunable plasmonic material suitable for THz antennas and presents the concept of solar light-trapping nano-receptors (SLTNR) as a sustainable power source. The overall research motivation, problem statement, objectives, and scope of the study are also discussed.

Chapter 2 – Literature Review

This chapter presents a detailed review of existing research on THz antennas, graphene-based tunable radiators, reconfigurable MIMO structures, band-notched UWB antennas, and pattern diversity techniques. It also includes studies on dielectric resonator antennas, frequency selective surfaces, plasmonic graphene strips, and nanoscale solar absorbers used for enhanced quantum efficiency. The chapter systematically identifies research gaps in tunability, power autonomy, integration of communication and energy-harvesting structures, and performance limitations in current THz antenna designs. These gaps justify the need for the proposed integrated graphene–SLTNR model.

Chapter 3 – Theoretical Background

This chapter covers the fundamental theoretical concepts relevant to graphene plasmonics, THz propagation, Kubo's formula for graphene conductivity, and the principles of surface plasmon resonance. It explains the electromagnetic theory essential for antenna operation, including impedance bandwidth, radiation efficiency, modal behavior, and frequency reconfigurability. Additionally, theoretical models of nanoscale light trapping, photon absorption enhancement, and photocarrier generation in thin-film solar structures are described to establish the analytical foundation of the proposed designs.

Chapter 4 – Design of Graphene-Based THz Antennas

This chapter describes the complete design methodology for graphene-based THz antennas, beginning with material selection, substrate optimization, and geometric modeling. It explains how tunability is achieved through variations in chemical potential and how plasmonic behavior enables ultra-compact antenna configurations. Various antenna structures such as dual-band radiators, MIMO elements, and filtering geometries are designed and simulated. The chapter includes detailed CST/HFSS/COMSOL setups used for achieving targeted bandwidth, gain, and reconfigurable behavior.

Chapter 5 – Solar Light-Trapping Nano-Receptor Modeling

This chapter focuses on the modeling and design of nanoscale solar light-trapping structures. It explains the working principles of nanowells, nanorods, metasurfaces, and graphene-disc-based absorbers used to enhance solar photon capture. Light-trapping theory, resonance engineering, and plasmonic absorption mechanisms are presented. The chapter develops the SLTNR model capable of providing nanoscale power suitable for graphene THz antennas, ensuring energy-autonomous operation in future communication devices.

Chapter 6 – Integration and Simulation

This chapter demonstrates the integration strategy for merging the graphene THz antenna with the solar light-trapping nano-receptor. It discusses structural compatibility, electromagnetic coupling effects, hybrid substrate behavior, and energy transfer characteristics. Full-wave 3D simulations are performed to study the performance of the integrated system, including tunability, gain enhancement, radiation pattern changes, and power-harvesting efficiency. The chapter concludes with parameter optimization and validation of the hybrid model’s feasibility for 6G applications.

Chapter 7 – Fabrication and Testing

This chapter provides a detailed explanation of the fabrication techniques required to produce the proposed antenna–SLTNR system. Processes such as CVD growth of graphene, lithography, nano-patterning, deposition, and layer transfer techniques are outlined. The experimental setup for THz characterization, solar absorption measurement, and impedance testing is described. Fabricated prototypes are evaluated to compare measured data with simulated results, verifying practical performance and limitations.

Chapter 8 – Results, Discussion, and Conclusion

This chapter presents all experimental and simulation results, including gain, bandwidth, tunability, MIMO performance, band-notch functionality, and light-trapping efficiency. It discusses the improvements achieved using graphene plasmonics and the SLTNR layer. The chapter concludes with a critical analysis of system-level performance and highlights how the proposed design addresses existing research gaps. Final conclusions and future research possibilities—such as flexible antennas, metasurface integration, and AI-driven adaptive THz devices—are also provided.

Chapter 9 – References

This chapter provides a comprehensive list of all research articles, books, conference papers, and technical reports cited throughout the thesis. The references include foundational works on graphene physics, THz antenna technologies, nano-photonics, SLTNR modeling, and 6G communication standards. The chapter follows a standard academic referencing style (IEEE) and ensures that all literature used in the research is properly acknowledged.

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